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THE METAMORPHISM OF GLACIAL DEPOSITS[1]

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INTRODUCTION

Glacial drift metamorphosed to a conglomerate has been studied in several parts of the world. A detailed description of such a conglomerate in South Australia, identified as a Cambrian tillite, has recently appeared;[2] glacial formations of the same period have been studied in China.[3] In India,[4] Africa,[5] and South Australia,[4] glacial conglomerates of Permian age have been carefully investigated.

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[1] Published by permission of the Ohio Geological Survey, but the author is responsible for the opinions expressed. Read before Section E of the American Association for the Advancement of Science at Baltimore, 1908.

[2] Rev. Walter Howchin, "Glacial Beds of Cambrian Age in South Australia," *Quart. Jour. Geolog. Soc.*, Vol. LXIV (1908), pp. 234–59. The same author made a preliminary report in 1901, *Trans. Roy. Soc. of South Australia*, Vol. XXV, p. 10.

[3] Willis, Blackwelder, and Sargent, *Research in China*, Vol. I (1907). Carnegie Institution, Washington.

[4] C. D. White, *American Geologist*, Vol. III (1889), pp. 306–11. Chamberlin and Salisbury, *Geology*, Vol. II (1906), pp. 632–35.

[5] C. D. White, *op. cit.*, pp. 303–6. Chamberlin and Salisbury, *op. cit.*, pp. 635–38.

The present brief inquiry is confined to glacial sediments of the Pleistocene period. The conclusion arrived at, from a field study of these sediments in central New York and in northern and central Ohio, is that locally, at least, the alteration of a part of the drift is under way, that is, it has reached an appreciable stage of metamorphism; furthermore, that this fact may be used in differentiating the drifts of some of the Pleistocene epochs.

In this paper the term "metamorphism" includes all alterations concerned in the transition from degradational products to solid rock again.[1] It is not possible to observe many stages in this cycle because of the fact that so far as present investigation goes, the glacial periods are separated by long lapses of time, and because of the further fact that most phases of metamorphism require a physical environment that precludes observation.

FIELD DATA

The glacial deposits that occasioned this study are characterized by the following features:

1. *Color.*—All the unmodified drift concerned is bluish; it is felt that this is the constant color of the deposits because the observations were made either along stream banks that were being undercut, thus giving fresh exposures, or along shore cliffs where the waves are undermining the drift. In most of the exposures the color condition is emphasized by contact with drift which differs in color; the usual association is a yellow and sometimes oxidized horizon of more recent glacial accumulation beneath which is the zone of bluish drift. So far as can be ascertained, the color is not dependent upon the content of the drift. The surfaces of the included bowlders, large and small, and the entire matrix of clay, are uniformly of a bluish cast. This characterization applies equally to these deposits in widely separated parts of Ohio as well as throughout a considerable region of central New York. Because of a lithological difference in the rock formations that were eroded, as shown by a study of the bowlders and pebbles in the drift, one would expect some variation in color; this, however, is not the case.

2. *Texture and structure.*—As is the case with nearly all types of

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[1] C. K. Leith, *Journal of Geology*, Vol. XV (1907), p. 313.

glacial deposits, we have here a great variety in texture. The till of some exposures is very fine, and quite free of even small bowlders; other exposures contain many, and large, erratics. More uniformity in texture, however, is found in the water-laid drift belonging to this study; usually, it is fine, even silty.

All these deposits apparently show the effects of great and long-continued pressure. They are dense in structure. This compactness is manifest in the angle at which the cliff-faces stand, not infrequently overhanging; also in the tendency of bowlders, showing on the surface of the cliffs, to hang even after more than half their mass has been exposed. In some cases I was able to satisfy myself, by tracing this hard horizon back from the cliff, that it constituted the proverbial "hard pan" of well-drillers. Furthermore, I have seen several dug wells being made, in which case there could be no doubt about the identity of this compact horizon and the bluish till.

3. *Obvious physical alteration.*—In several cliff-exposures the contact between this hard deposit and the superjacent drift is a series of sags and swells representing either an irregular deposition of the subjacent material or its unequal erosion later (Fig. 1). But the relation of the inequalities precludes subaërial erosion; the irregular surface is either genetic, or it was produced by the erosion of overriding ice.

Contortion and folding is observed particularly in the water-laid deposits (Fig. 2). This alteration has been studied in material varying from silt to rather coarse sand. I have examined many exposures, both modified and unmodified, which show jointing and faulting (Figs. 3, 4, 5). In no case was I able to show conclusively a displacement of more than three inches, and this maximum displacement was always in the water-laid drift. It is quite impossible to measure movement along a fault-plane involving only till. On the theory that every joint is a fault,[1] we may assume a displacement even though it cannot be measured. In all exposures of till thus altered, the joints are nearly vertical, and in systems (Fig. 6). In the water-laid deposits this characterization is less clear. It should be stated, furthermore, that along most of the joint-planes or fault-

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[1] G. F. Becker, *Bulletin of the Geological Society of America*, Vol. IV (1893), p. 72.

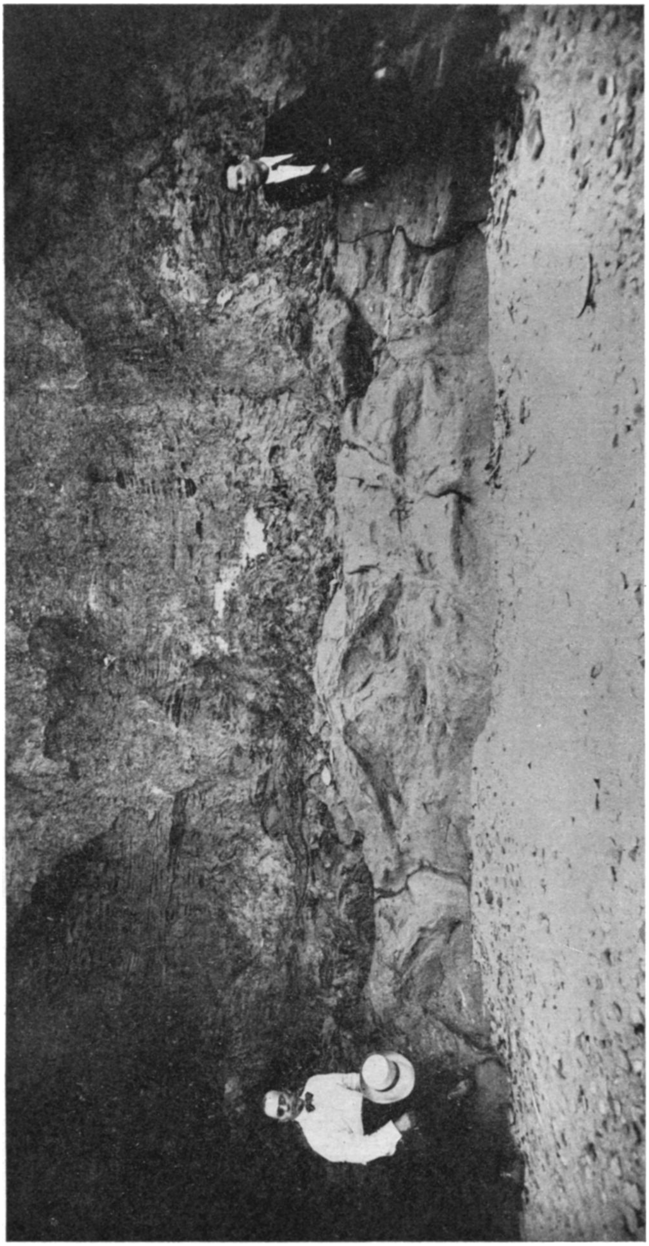

FIG. 1.—Buried valley west of Cleveland. At the base is bluish till, apparently ice-eroded; above is compressed and slightly distorted silt.

planes there has taken place either a secondary alteration or a deposition from percolating water (Fig. 2). In some cases this secondary deposit has weathered away more rapidly than the wall material; in others, less rapidly.

4. *Weathering.*—Leaching in a relatively short time removes carbonates, especially from surface deposits. Only at a considerable distance from the top do we often get evidence of carbonates in the superjacent drift. This leaching by ground water is the first step in the cementation process always going on at lower horizons. The bluish compressed drift invariably shows the presence of calcium carbonate. This fact does not imply that the drift had never lost its carbonates through leaching; it means only that now this particular cement is present, deposited probably from solution. No further observation was made to determine the cements or other chemical content of this dense drift. It is tentatively assumed that the universal bluish color is a result of alteration, though it cannot be disproved that this drift in both New York and Ohio was not bluish from the time it was deposited, but the force of this possibility is somewhat lessened by the fact that there is considerable difference in the content of the drift of these areas; it is assumed, further, that this color probably represents a chemical alteration accompanying metamorphism, a change brought about, under particular conditions, by ground water in unconsolidated sediments. The nature of these conditions will be discussed later.

The superjacent yellow till usually shows the results of weathering, especially near the surface; but in all parts there is evidence of leaching.

AGENCIES OF ALTERATION

Normally most of the changes going on in the regolith are due to pressure and to chemical reactions. The pressure is that of the superincumbent mass which varies directly with the depth. Chemical reactions are chiefly associated with water which is always a solvent, but the water of glacial drainage, since it comes in contact with such a wide range of rocks, is highly solvent and has capacity for other chemical reactions.

Chemical.—Outside of arid regions, sediments contain a good deal

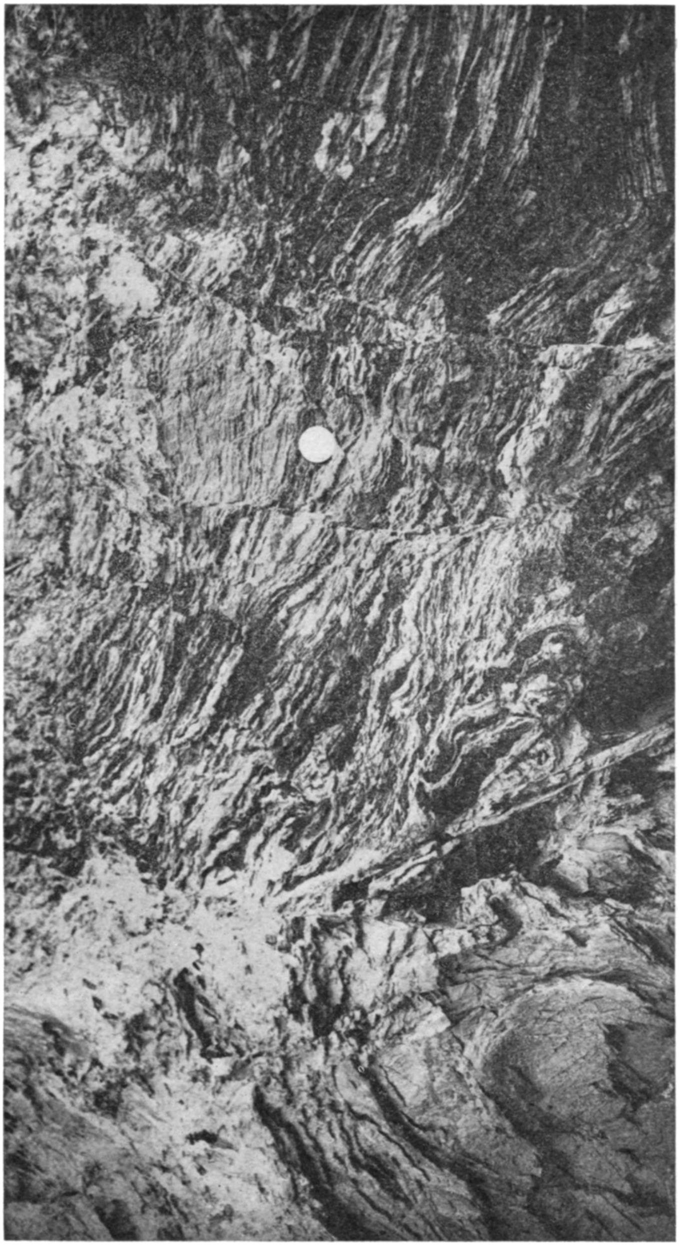

FIG. 2.—Deposits in a buried river valley west of Cleveland; this material was crumpled and distorted; later it was faulted; vein deposits occupy the fault-planes.

of water. In all climates circulating ground water exists at some depth; the more humid the climate, the higher is the ground-water level. It is probable, however, that a special condition exists in sediments subjacent to an ice-cap; here, on account of the constant melting of the basal ice caused by radiation from the earth,[1] the supply of water is so great that a condition of saturation exists in these sediments. This condition of saturation was certainly the case during both the advance and retreat of the ice-sheet within the north-sloping side of the St. Lawrence drainage basin. This northward slope in conjunction with the wall of ice caused a ponded condition of drainage. Beneath these bordering lakes, sediments were always in a condition of saturation.

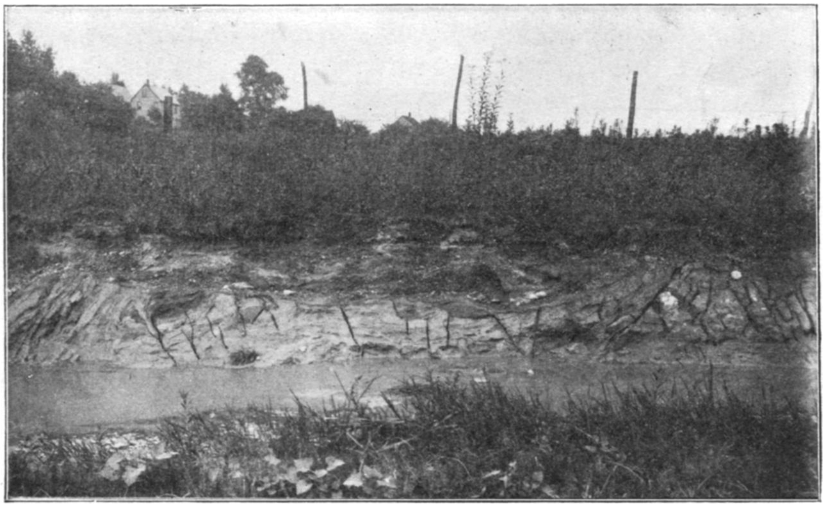

FIG. 3.—Disturbed and faulted bluish till exposed along Dugway Brook, Cleveland.

Underneath an ice-sheet, it is reasonable to suppose that oxidation is subdued, but even in the absence of atmosphere, sulphides may be slowly changed to sulphates. Since this glacially accumulated rubbish may contain constituents previously weathered, it is possible that deoxidation also takes place.

Throughout the distance between the Mohawk Valley in New

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[1] Chamberlin and Salisbury, *Geology*, Vol. I (1904), p. 263.

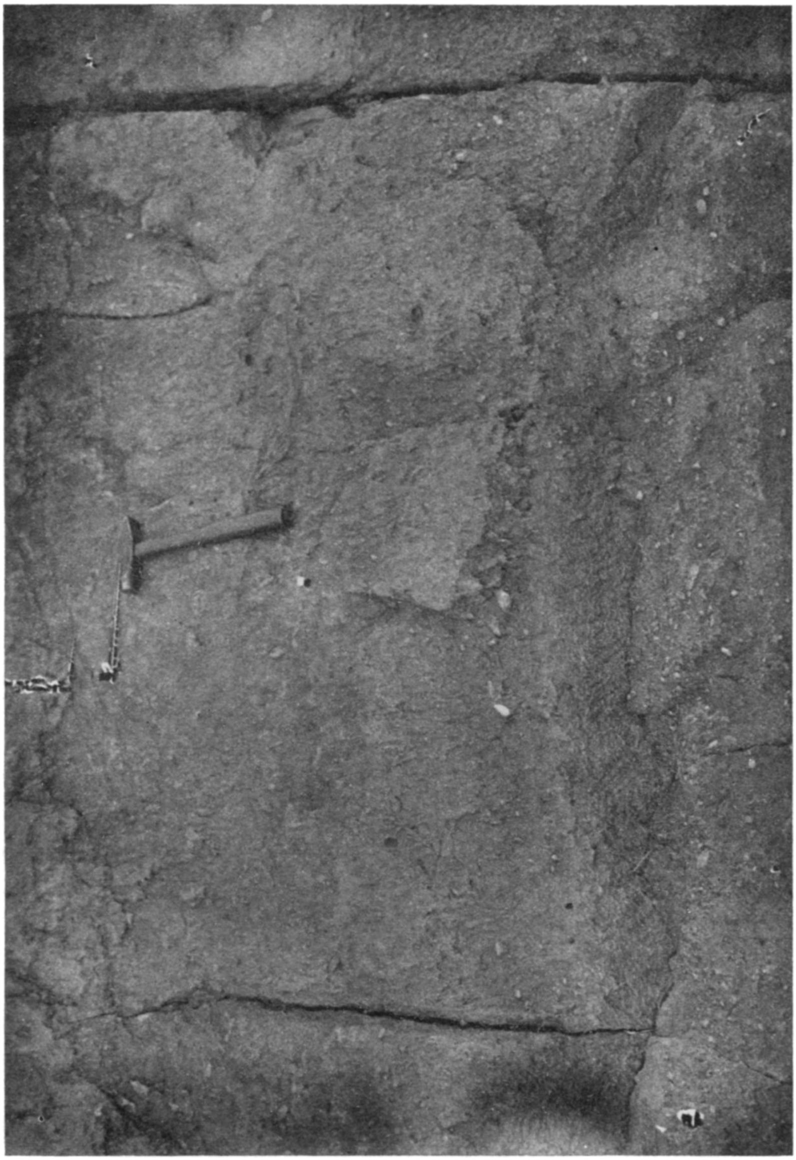

Fig. 4.—Jointed bluish till on shore of Lake Erie at Conneaut, O. The cliff-face is a joint-plane at right angles to the two conspicuous joints.

York state and Michigan at the western end of Lake Erie, limestone formations come to the surface. These outcrops suffered degradation by the ice-sheet. Other limestone horizons farther north, in part of this distance, also contributed to the glacial load of débris. This content of limestone in glacial sediments was partly dissolved even by the cold water; no rock-forming constituent is more easily affected by water. The resulting carbonated water actively attacked the silicate minerals at least. Solution and later precipitation is always an accompaniment of ground-water circulating through glacial sediments, and further reactions will give different solutions.

The decomposition of rock-constituents is usually accompanied by hydration. This is almost invariably the case in oxidation and carbonation. In unconsolidated materials beneath an ice-cap hydration would be an active agent in alteration.

Pressure.—In the deeper-seated areas of the fragmental zone of the earth's crust, pressure has long been regarded as playing an active part in the alteration of rock. In the case of the superficial sediments under discussion there appear to be three sources of pressure:

1. The weight of drift overlying a given horizon in a mass of sediments exercises a compressive force; in the deeper-buried sediments this force is stronger. In consequence of this compression there is greater facility in capillary action, that is, waters move more slowly through these sediments, and precipitation is increased.

2. During the continuance of an ice-invasion, the weight of the ice itself bore down on the unconsolidated materials, thus acting as a factor in their alteration. In discussing this, however, it must be granted that an ice-sheet degrades, first of all, the regolith. It is a fact nevertheless that in certain localities, some of the previously aggraded sediment was not removed by ice.[1] These deposits may be the drift of an earlier ice-invasion; in any case, wherever not removed, it was subject to the great weight of the ice-sheet. This weight can be computed only approximately. Some observations have been made on which are based conclusions in reference to the surface slope of ice-caps; this data includes a study of both existing

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[1] R. S. Tarr, *American Geologist*, Vol. XXXIII (1904), p. 287. H. L. Fairchild, *Bulletin of the Geological Society of America*, Vol. XVI (1905), pp. 53–55. F. Carney, *Journal of Geology*, Vol. XV (1907), pp. 579, 580.

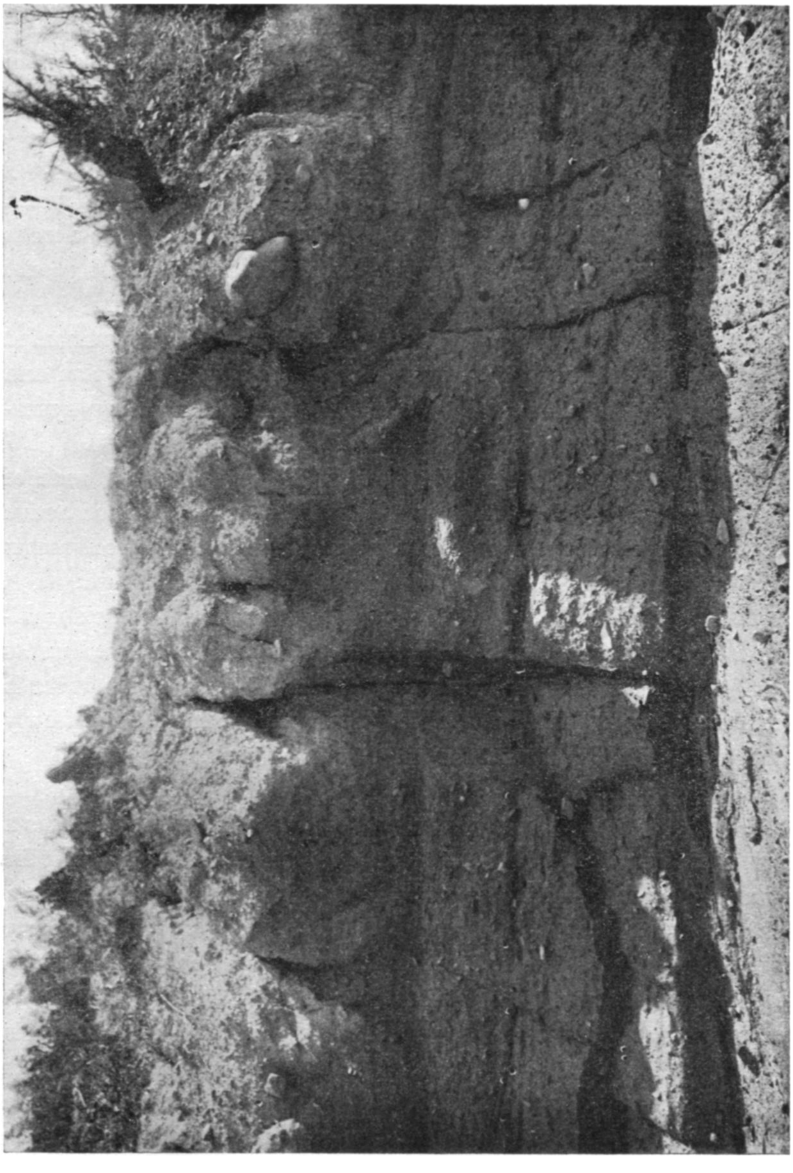

Fig. 5.—Jointed bluish till on shore of Lake Erie, east of Cleveland.

ice areas and bands of drift constructed by former ice.[1] A conservative estimate of the depth of Wisconsin ice over the Erie basin is at least 2,000 feet. This figure is based on two considerations: the present difference in level between Lake Erie and altitudes south that were covered by ice is about 800 feet. The ice reached south of the Erie basin approximately 200 miles; if its surface sloped even six feet per mile, this would represent a depth of 1,200 feet which, plus the 800 feet due to the difference in altitude, makes approximately 2,000 feet. The basal pressure per square foot for clear ice of this thickness would be 115,500 pounds.

In New York state, there is a greater difference in altitude, even when we neglect the overdeepened portions of the major Finger Lake valleys. The range in altitude alone would give 1,500 feet of ice; this, in connection with the surface slope of the ice, would give a depth of approximately 2,500 feet, which represents a basal pressure per square foot of over 144,000 pounds. Both these computations, it is noted, are for clear ice. Knowing that the ice-sheet must have carried constantly some drift, these figures undermeasure, perhaps, the real pressure. That the subjacent deposits would be compressed by the weight of this ice is undebatable.

Adams has shown that a condition of rock-flowage was induced in marble by a pressure of about 18,000 pounds per square inch.[2] The pressure on the sediments, as discussed above, is in either case more than 9,000 pounds per square inch.

Another possible factor associated with the question of pressure is the development of heat. Even the laggard motion of an ice-sheet represents energy which through basal interference is converted into heat. This heat may have no other manifestation than the wastage of ice near the friction zone. Whether a dead load upon compressible matter evolves heat in the absence of appreciable movements along planes developed in this matter is a question on which the writer is not informed.

3. It is thought, furthermore, that pressures are evolved by chemical changes going on in this drift. Such pressure is an accompaniment of hydration when the hydrated mineral is confined as must be the

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[1] Chamberlin and Salisbury, *Geology*, Vol. III (1906), pp. 356–58.

[2] F. D. Adams, *Bulletin Geological Society of America*, Vol. XII (1901), p. 457.

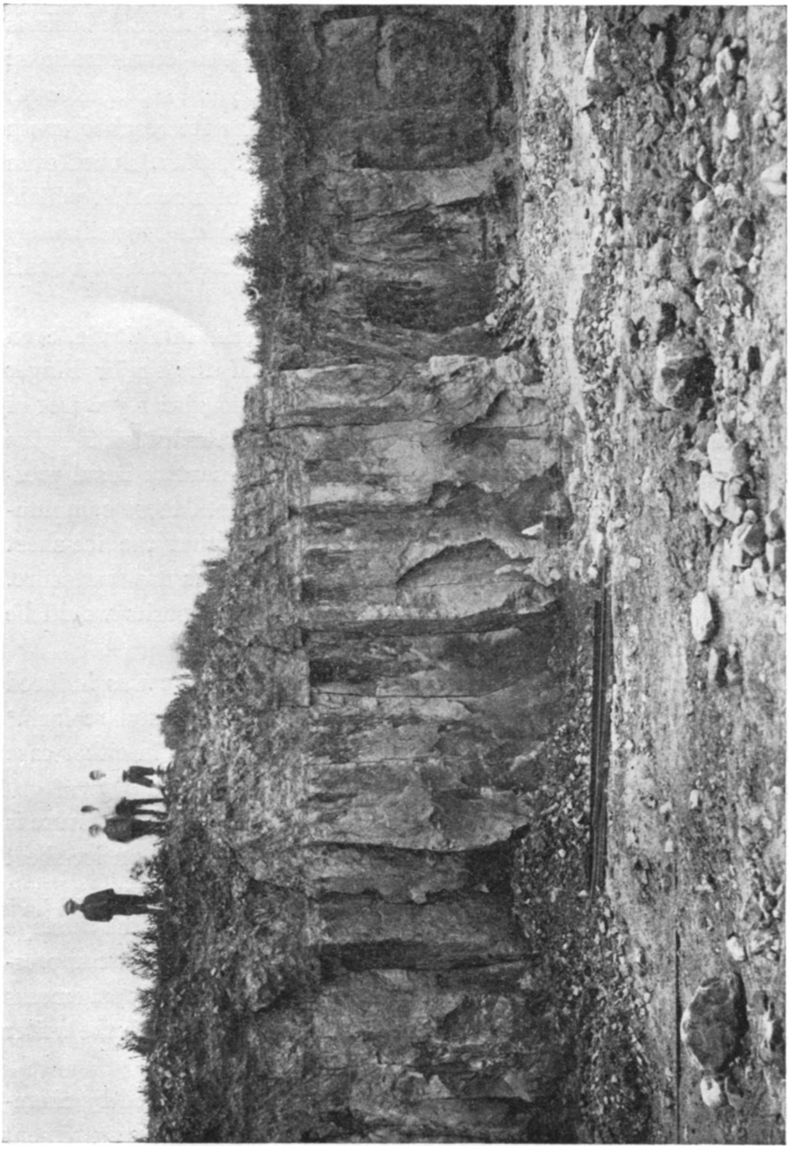

FIG. 6.—Water-laid drift overlying bluish till which contains two systems of vertical joints. This till is very stony, mostly limestone.

case in drift subjacent to a burden of at least 9,000 pounds per square inch. Other chemical changes also tend to increase the bulk of the minerals being altered.

SUMMARY

In defining its age and origin the most suggestive feature of this drift is its color which is constant over widely separated areas. The folding, jointing, and faulting might be caused by Wisconsin ice readvancing over drift it had recently deposited; faulted sediments subjacent to till of such a readvance are shown in Fig. 7.

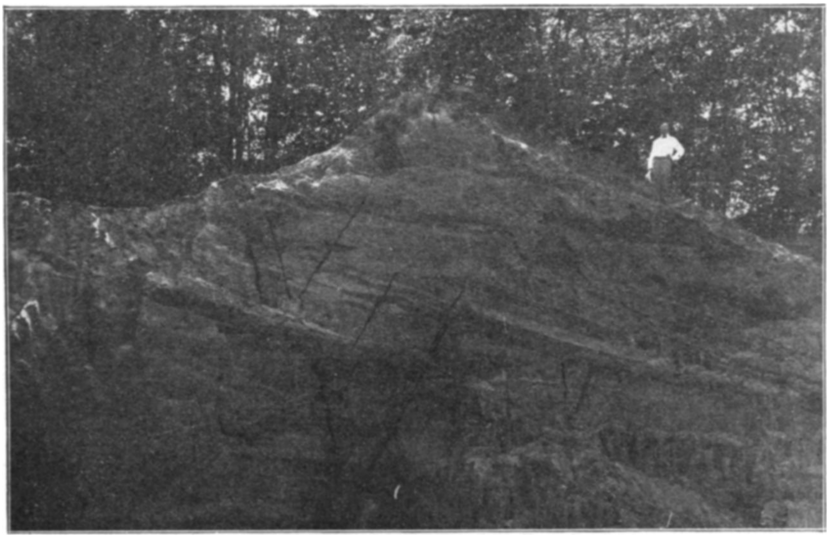

FIG. 7.—Faulted glacial gravels. Yellow till has been removed from the top.

It is possible that the bluish till is the product of the oncoming Wisconsin ice. If the pressure of an ice-cap is the most active agent of alteration, and the time factor is secondary, it is even probable that both the bluish and yellow drifts are Wisconsin; but the following observations tend to diminish this probability:

About three miles northeast of Newark, O., along Shanee Run, and again two and one-half miles southeast of Newark along Quarry Run, I have seen the same bluish till, at the former outcrop in contact with the yellow drift, at the latter showing only in the bed of the stream where it forms a riffle. These localities are just within the margin of the Wisconsin drift, where the ice was attenuated as well as short-lived. It is certain that in these two cases time has been the important factor in the alteration; no great mass of ice ever stood here for even a short period. If this hard bluish till was deposited by Wisconsin ice, its color is genetic; but on this hypothesis it is difficult to understand why the superjacent drift is yellowish, and the line of division is so sharp.

But there can be no question that the old valley of Rocky River, west of Cleveland, was buried by a pre-Wisconsin ice-invasion, presumably the Illinoian. The bluish till in this buried stream-course is apparently identical with the dense drift referred to in central Ohio and New York.

These facts suggest the following conclusions:

1. Glacial deposits, regardless of their constituents, when buried for a long time appear to become compact, and bluish in color. This assumption does not disregard the possibility that some deposits have always been bluish. The dozens of exposures studied in both states show a great variety of rock-constituents, as well as wide variation in the general texture of the drift; this color is constantly noted in drift ranging from fine silt to an extremely stony till (Figs. 1, 2, and 6[1]). I have nowhere noted a gradual blending from one color to the other, nor streaks of the yellow penetrating the bluish, as has been described in the Central West.[2] It is very likely that upon sufficient exposure to weathering agents the blue till would become lighter in color; but because of its indurated condition it weathers less rapidly than does the superficial Wisconsin drift.

2. An ice-cap passing over glacial sediments, particularly till, develops in it joints and faults (Figs. 2–4) either because the till on account of inconstancy in structure yields differentially to the weight, or because differential strains are induced by topography; these fracture lines are approximately vertical (Figs. 5, 6). I have observed

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[1] Cf. *Journal of Geology*, Vol. XV (1907), pp. 575, 577, for other pictures illustrating the same variation in texture.

[2] F. Leverett, *Monograph XLI*, U. S. Geolog. Surv. (1902), p. 272. *Ibid.*, *Monograph XXXVIII*, U. S. Geolog. Surv. (1899), p. 28. W. H. Norton, *Iowa Geological Survey*, Vol. IX (1898), pp. 480–82.

this jointed condition of till in central and northern Ohio, and in New York along creeks tributary to the outlet of Keuka Lake.[1]

3. The altered drift described in this paper contains abundant carbonates, probably deposited from circulating ground water, whereas carbonates are either absent or less conspicuous in the superjacent drift of later origin. This difference between the two drifts is apparent even when tests are made near their contact; the observation holds for exposures studied in all the areas under consideration.

4. The color in the case of the drift above described, its indurated condition, and the jointing appear to be associated with the change or metamorphism which develops tillite from glacial drift.

5. I believe that so far as the regions considered in this paper are concerned two Pleistocene epochs are indicated by a contact of the bluish and yellow till.

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[1] *Journal of Geology*, Vol. XV (1907), pp. 583, 584.